Prospects for a precision timing upgrade of the CMS $PbWO_4$ crystal electromagnetic calorimeter for the HL-LHC

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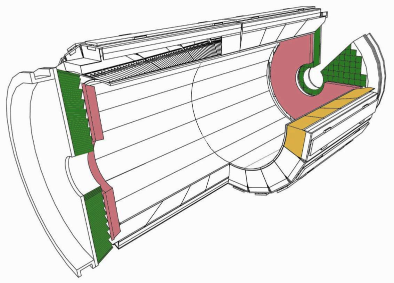
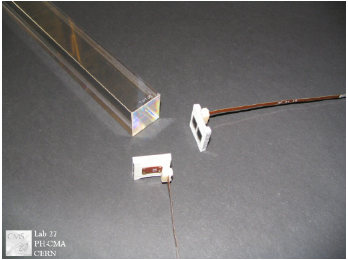
The CMS Electromagnetic Calorimeter (ECAL)



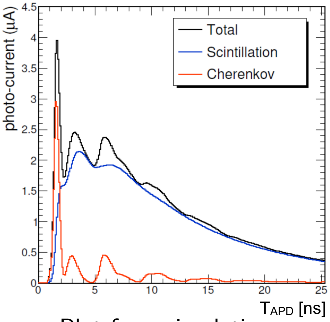
- Homogeneous, compact, hermetic, fine grain $PbWO_4$ crystals calorimeter
- Designed for **excellent energy resolution** (< 1 % for 60 GeV γ)

- Divided in two regions:
  - $\rightarrow$ **Barrel** (EB): $|\eta| < 1.48$, 61200 channels, APD readout
  - $\rightarrow$ 2 **Endcaps** (EE): $1.48 < |\eta| < 3$, 14648 channels, VPT readout
- **Preshower** detector:
  - $\rightarrow$ $1.65 < |\eta| < 2.5$
  - $\rightarrow$ lead/ silicon strips detector
  - $\rightarrow$ aid π^0/γ discrimination

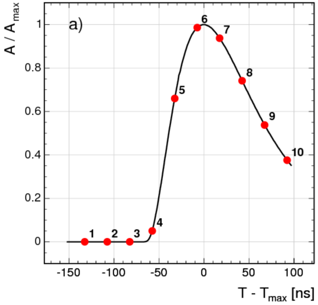


The ECAL $PbWO_4$ crystals and readout

- Design ECAL requirements:
  time jitter < 1 ns to ensure good energy resolution
- $PbWO_4$ fast scintillator for an EM shower:
  - → $\sim$ **90 % light** emitted within **25 ns**
  - → $\sim$ 10 % contribution from Cherenkov emission



Plot from simulation

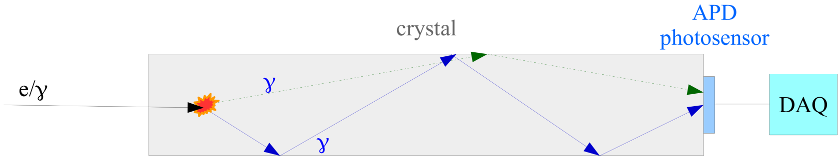


- Current pulse shaping optimized for the LHC conditions → to change at HL-LHC
  - → **43 ns** electronics **shaping time**
  - → sampling at 40 MHz
- Arrival time information extracted from pulse shape

Single channel time resolution

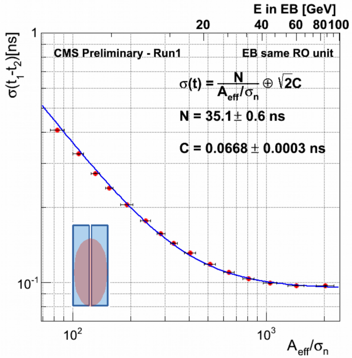
Several contribution to single channel timing resolution:

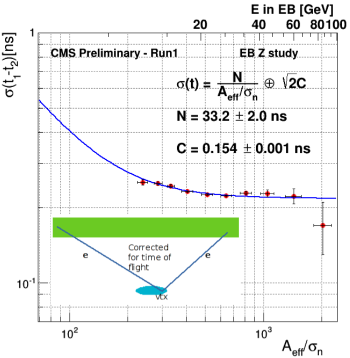
- Electromagnetic shower development fluctuations:
  - $\rightarrow$ longitudinal shower fluctuations
  - $\rightarrow$ optical transit time spread
- Photodetector + electronics
  - $\rightarrow$ photodetector rise and transit time
  - $\rightarrow$ dark current rate and noise
  - $\rightarrow$ electronics shaping time
- DAQ clock distribution



Current time resolution

- $PbWO_4$ crystals **intrinsic time resolution** measured at test beam:
  - $\rightarrow$ $\sim$ **20 ps constant term**
- In-situ measurements:
  - $\rightarrow$ **close-by crystals** (same readout unit) of the same shower $\sim$ **70 ps**
  - $\rightarrow$ crystals in **different clusters** with Z$\rightarrow$ee events $\sim$ **150 ps**

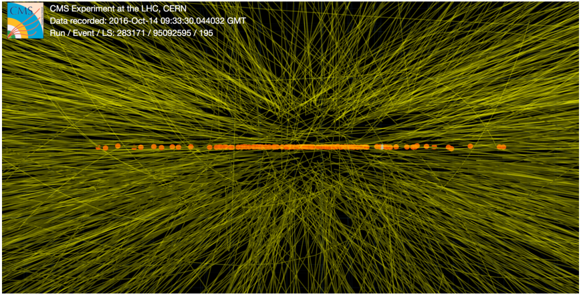




The HL-LHC

- HL-LHC ultimate performance:
  - Instantaneous peak luminosity $\mathcal{L} = 7.5{\cdot}10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
  - $\text{L} = 4500\ \text{fb}^{-1}$ in 10 years
- 6 times higher level of radiation than at LHC
- Mean number of interactions per bunch-crossing from $50 \rightarrow 200$
- Degradation of object reconstruction performance

  $\rightarrow$ necessary upgrade of CMS sub-detectors



Event recorded during special high pileup fill with $\sim$ 100 concurrent interactions

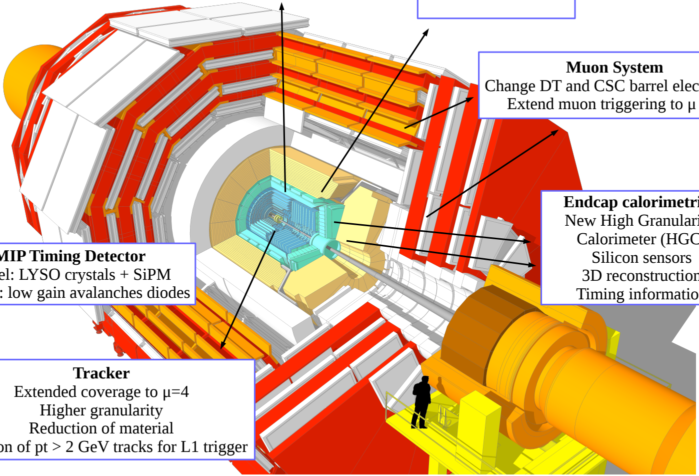
CMS Upgrade overview

Trigger
Track information at L1
L1 Trigger latency 12.5 μs
L1 output 750 kHz
HLT output 7.5 kHz

ECAL Barrel
Upgrade of electronics
Operate at lower temperature

HCAL Barrel
New electronics

Muon System
Change DT and CSC barrel electronics
Extend muon triggering to μ = 3



Endcap calorimetries
New High Granularity
Calorimeter (HGC)
Silicon sensors
3D reconstruction
Timing information

MIP Timing Detector
Barrel: LYSO crystals + SiPM
Endcap: low gain avalanches diodes

Tracker
Extended coverage to μ=4
Higher granularity
Reduction of material
Selection of pt > 2 GeV tracks for L1 trigger

ECAL Barrel Upgrade overview

ECAL electronics **upgrade mandatory to meet HL-LHC L1 trigger requirements**

- **Increase latency**: 4.6 μs $\rightarrow$ 12.5 μs
- **L1 accept rate**: 750 kHz

ECAL electronics upgrade key points:

Trigger

- Provide **crystal by crystal information at L1** trigger (currently 5x5 crystals granularity)
  - $\rightarrow$ enhance spike rejection
  - $\rightarrow$ improve objects identification

Energy resolution

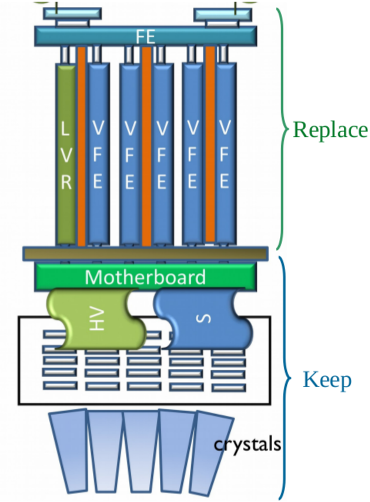
- Reduce APD noise due to radiation damage
  - $\rightarrow$ **cooling of crystals and photodetectors** 18°C $\rightarrow$ 9°C

Precision timing

- Goal: **30 ps time resolution** for deposits with E$>$ 50 GeV (photons from H$\rightarrow \gamma\gamma$ decay)

ECAL barrel upgrade

- Keep the **same crystals and APDs**
- **Replace Very Front-End (VFE), Front-End (FE) and off-detector electronics**
- **Upgrade VFE** electronics:
  - → dual gain Trans Impedance amplifier (TIA)
  - → preserve a **fast signal** to optimize time resolution
  - → **shorter shaping time** (43 ns → 20 ns)
- **ADC sampling** increased to **160 MHz**
- CMS clock distribution key role
  - → ensure $<$ 10 ps stability across CMS

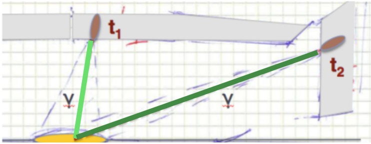


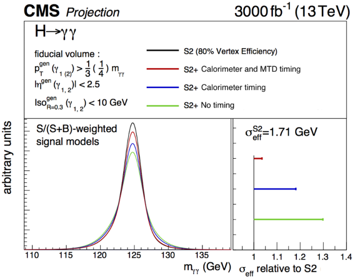
More in talk by S. Pigazzini: "The CMS ECAL Upgrade for Precision Crystal Calorimetry at the HL-LHC "

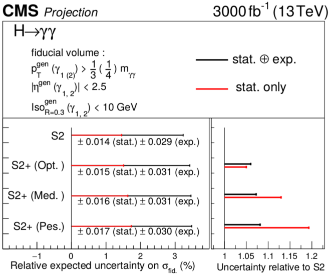
Benefits from ECAL precision timing

Benefits from ECAL precision timing probed on $H \rightarrow \gamma\gamma$ benchmark channel

- **Resolution on vertex z** position $<$ **1 cm**
  $\rightarrow$ **negligible impact on $m_{\gamma\gamma}$** resolution
- Currently determined exploiting recoiling tracks: $\epsilon \sim 80$ %
  - $\rightarrow$ drop to $\sim$ 30% at HL-LHC
- **vertex z** determined via γ **triangulation**
  - $\rightarrow$ recover part of inefficiency: $\epsilon \sim 50$ %







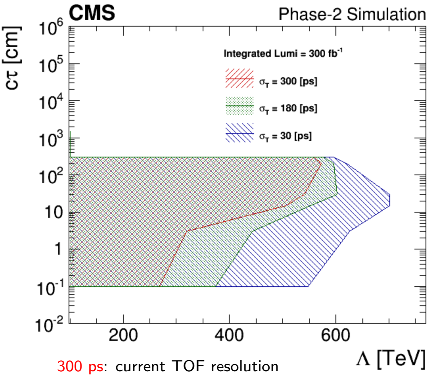
Benefits from ECAL precision timing

Long-lived particles predicted by many BSM theories

- Several experimental signatures featuring **delayed photons**
- Simulation study performed on $\tilde{\chi}_1^0 \rightarrow \tilde{G} + \gamma$

- **Photon time of arrival exploited to identify the signal**
- Analysis benefit from ECAL precision timing

  $\rightarrow$ **increase sensitivity to short lifetime and high mass neutralinos** (green region in the plot)



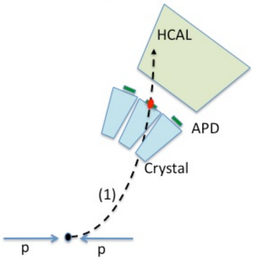
300 ps: current TOF resolution

180 ps: TOF resolution with ECAL timing upgrade

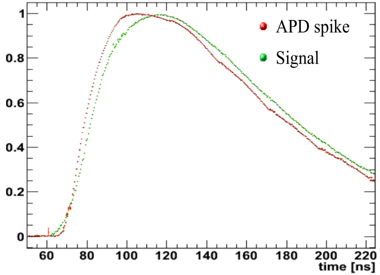
30 ps: TOF resolution with MIP timing detector

Anomalous APD signal mitigation

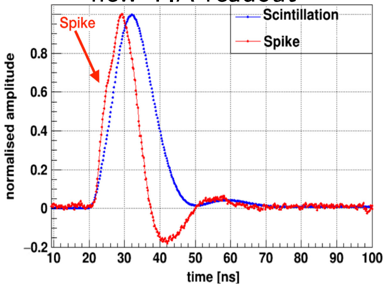
- Hadron interaction in APD
  → anomalous signals (*spike*)
  - → **faster pulse** than scintillation signal
  - → exploit **pulse shape for discrimination**



current readout



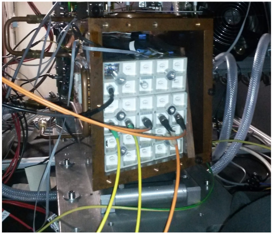
new TIA readout



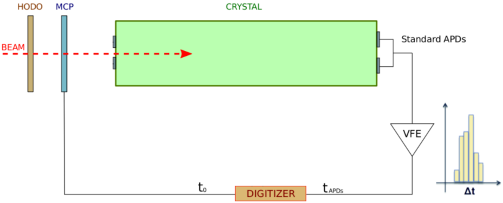
Test Beam campaigns

- Test beam performed in 2015, 2016, 2017 @ CERN SPS
  - → assess $PbWO_4$ intrinsic timing capabilities
  - → test performance with the upgraded electronics

- **5x5 matrix of ECAL crystals + APD**
- Different VFE configurations
- Signal readout by **fast digitizer** (CAEN V1742, **5 GS/s**)
- **Time information extracted from fit of the pulse shape**



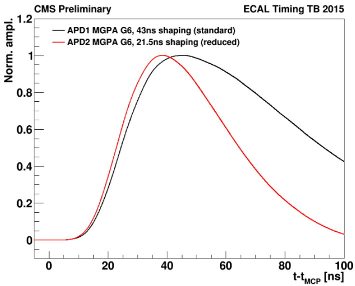
- **Micro-channel plates** (MCP) detector to provide **time reference** ($\sigma_t \sim 20$ ps)
- Time resolution extracted from gaussian fit of the t_{MCP} - $t_{crystal}$ distribution

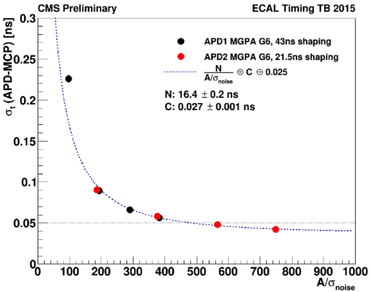


2015 Test beam results: impact of shaping time

- Employed **current VFE electronics**
- **Compared performance with current (43 ns) and reduced (21.5 ns) shaping time**
- Shorter shaping time $\rightarrow \sim$ factor 2 gain in A/σ_{noise} (signal/RMS noise)
- CMS in situ: **$A/\sigma_{noise} \sim$ 800 for a 50 GeV EM shower**

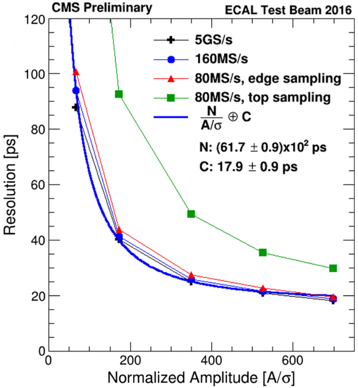
  $\rightarrow$ **$\sigma_t < 50$ ps**





2016 Test beam results with new electronics prototype

- Test performance of **prototype VFE with TIA component**
- Lower sampling frequency emulated at analysis level
  - → **ultimate performance already with 160 MS/s sampling**
- $\boldsymbol{\sigma_t \sim 30}$ **ps for** $\boldsymbol{A/\sigma = 250}$
  - → 25 GeV at HL-LHC start (100 MeV noise)
  - → 60 GeV at HL-LHC end (250 MeV noise)



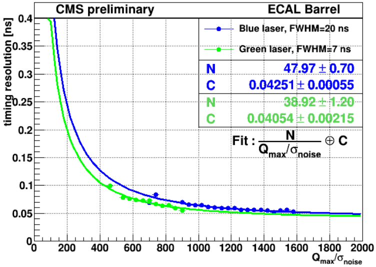
Summary

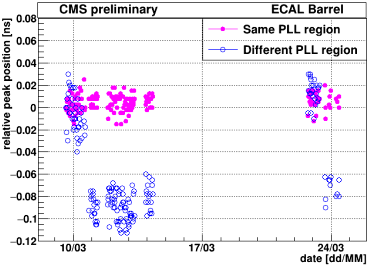
- The HL-LHC will be a challenging experimental environment for the LHC experiments
  - → CMS detector upgrade necessary to fully exploit the amount of data provided by the HL-LHC
- Precision timing powerful means through which mitigate pileup effects
- ECAL barrel electronics upgraded to cope with HL-LHC conditions:
  - → possibility to include precision timing for high energy EM showers
  - → goal: 30 ps time resolution for EM showers with $E > 50$ GeV
- Intrinsic $PbWO_4$ time resolution and performance of new readout tested at test beam
  - → 30 ps time resolution achieved during test beams

Additional Material

Clock impact on ECAL time resolution

- **Clock distribution checked exploiting laser system**
- Many crystals illuminated at the same time **across different readout units**
- One crystal taken as reference (t_{ref})
  - $\rightarrow$ timing resolution from gaussian fit to $\mathbf{t_{crystal}} - \mathbf{t_{ref}}$
- Timing resolution of $\sim$ **40 ps** measured across whole ECAL
- Clock distribution **instabilities** between **different readout units**
  - $\rightarrow$ $\sim$ 100 ps shift in signal peak position
  - $\rightarrow$ Instabilities occur after system resets





The CMS clock distribution

- Common CMS effort for precise clock distribution for Phase 2 upgrade
- Goal: 10-15 ps RMS jitter
- Two approaches being investigated:
  - $\rightarrow$ LHC clock encoded within the lpGBT control links
  - $\rightarrow$ dedicated clock fibers + fan-out chips
- Slow variation of phase monitored and calibrated in-situ from minimum bias events